

Kick-off Meeting with Sponsors

Convened at:

NASA Glenn Research Center

Jerry Seitzman

November 18, 2002

ENABLING TECHNOLOGIES

- Pursue basic technology areas with potential applications to wide range of aeropropulsion issues
- **Actuators**
 - Combustion driven actuators for mixing control
 - Plasma augmentors for combustion
- **Diagnostics and MEMS Sensors**
 - Passive, wireless MEMS sensors
 - Turbulence and hot streak diagnostics in turbines
- **Nanotechnology**
 - Nanomaterials for sensors
 - Nanometallic fuel additives

Combustion-Driven Actuators for Mixing Control

Glezer, Neumeier, Jagoda (Georgia Tech)

Science & Technology Objective(s):

- Develop innovative, **combustion-based fluidic actuators** for mixing control, e.g., in
 - combustors for reduced emissions (Task 2.3.2)
 - free jets for noise reduction (Task 2.3.4)

Collaborations:

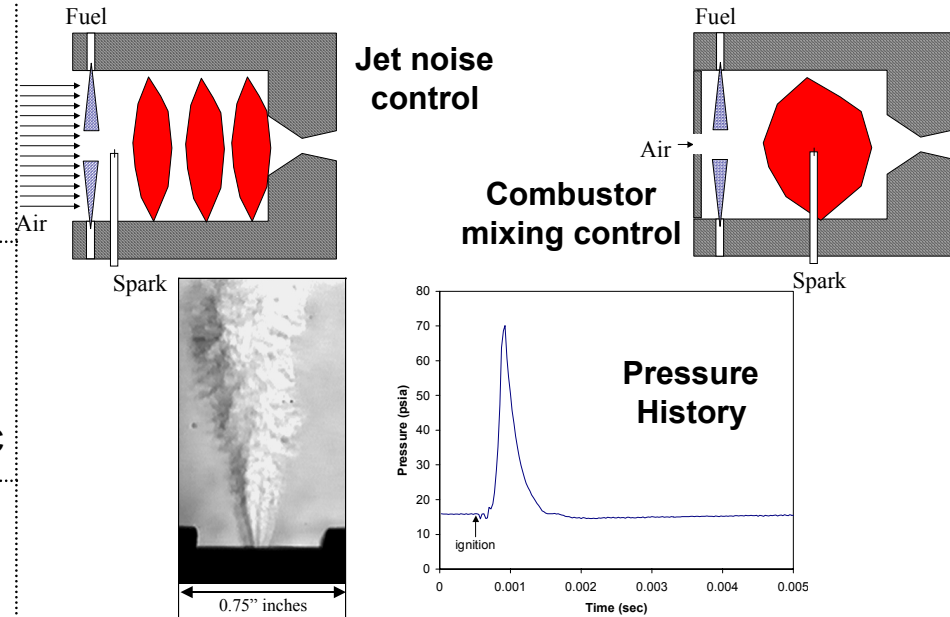
- Government –ARL, AFRL
- URETI –Combustor control, Noise control
- Industry – Val Kibens and William Bower (Boeing)
- Synergism with existing programs–ARMY MURI, DARPA MAFC

Proposed Approach:

- Actuator performance analysis
- Assessment of required momentum for combustor and free jet applications using existing large scale mechanical hardware
- Parametric investigation of actuator performance, scaling and preferred dimensional configurations
- Characterization of actuator jet
- Demonstration on combustor and jet simulators

NASA Relevance/Impact:

- **Reduce emissions**
 - Meeting NASA emission goals for subsonic aircraft
 - Enabling acceptable emissions for supersonic transport
- **Meet NASA jet engine noise reduction goals**



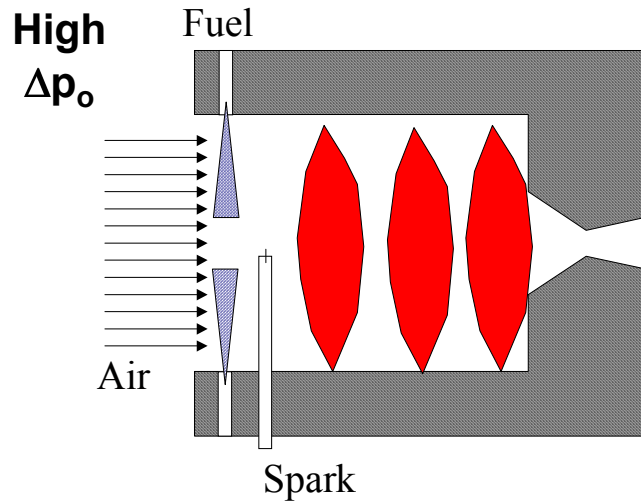
Milestones/Accomplishments:

- Establishment of required actuation performance in emission and noise control applications with existing subscale experimental facilities/mechanical actuators
- Analysis of combustion-based actuation to meet the established requirements
- Design of prototypical experimental setup
- Actuator performance characterization
- Demonstration of combustion based actuation on subscale jet and combustor simulators

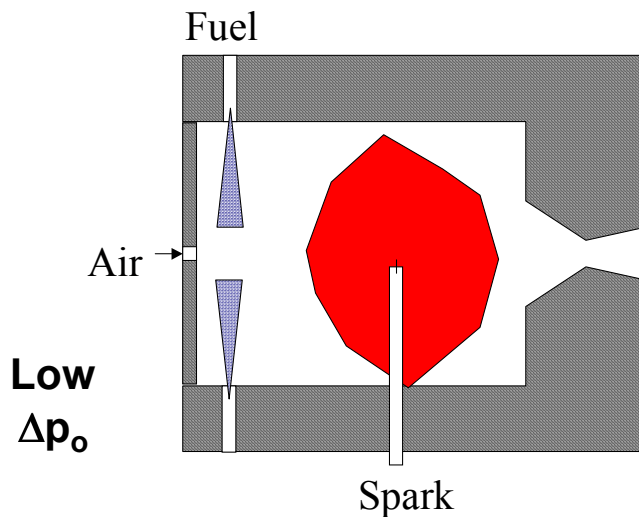
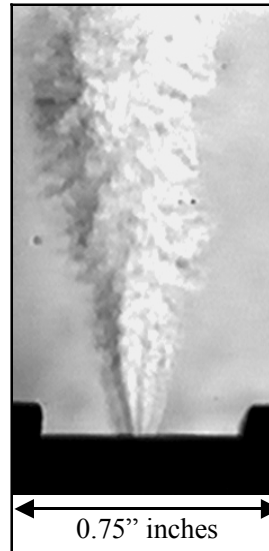
Combustion-Driven Actuators for Mixing Control

Concept - Applications Issues

Glezer, Neumeier, Jagoda (Georgia Tech)

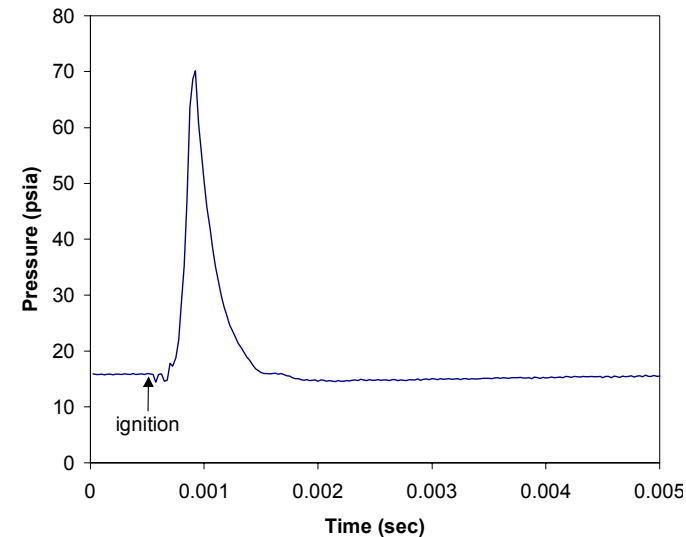


Jet Noise Control



Combustor Mixing Control

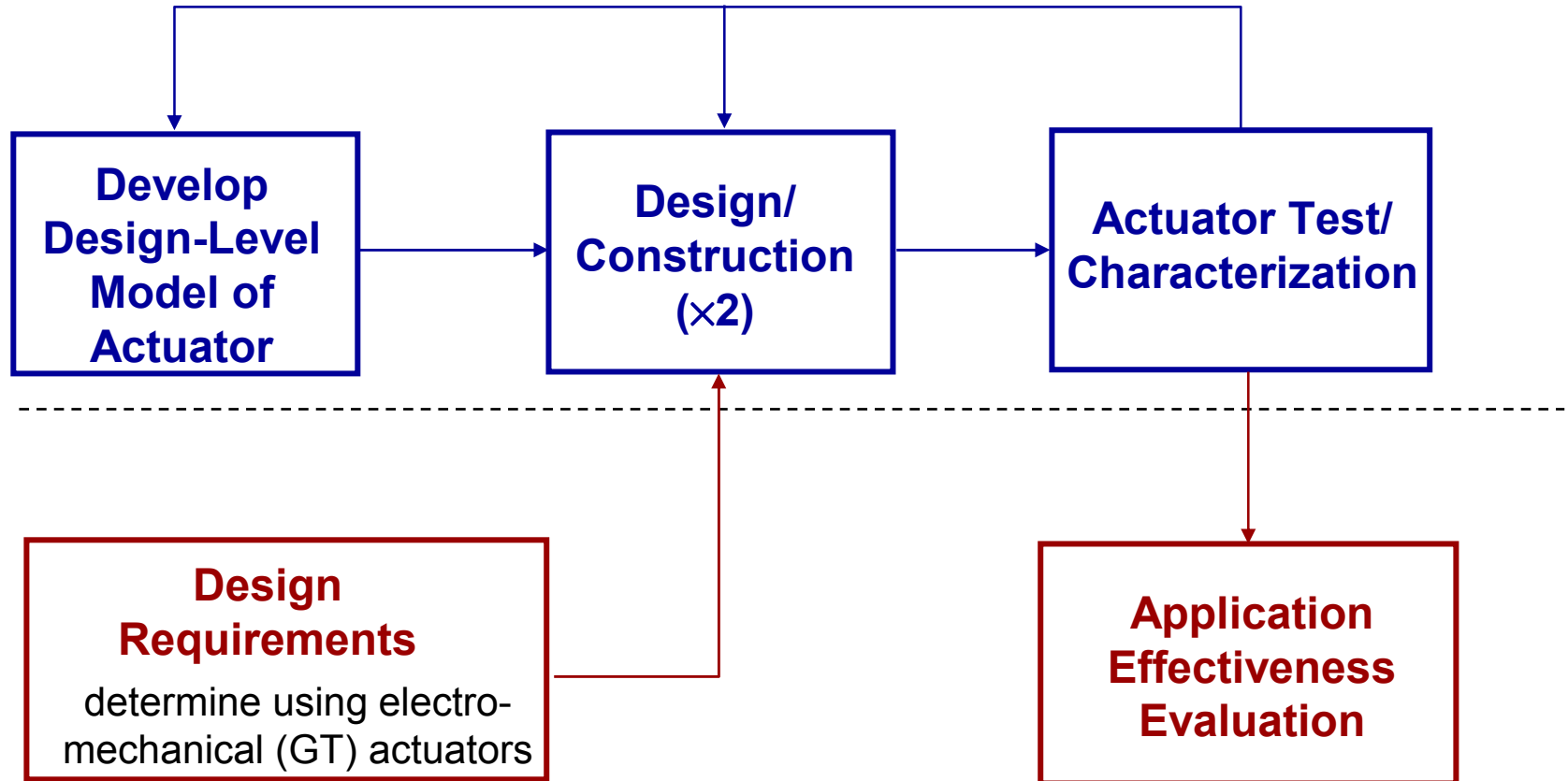
Pressure History



Combustion-Driven Actuators for Mixing Control

Proposed Approach

Glezer, Neumeier, Jagoda (Georgia Tech)



Interactions with:

- **Combustor Control**
- **Noise Control**

Enabling Technologies - Actuators Plasma Augmented Combustion

Jagoda and Menon (Georgia Tech)

Science & Technology Objective(s):

- Develop **low power** arc/corona **discharge** to **stabilize lean flames**
- Develop distributed arc/**fast-response** **relight system**
- Develop **advanced simulation tool** to predict plasma augmented combustion and flame stabilization

Collaborations:

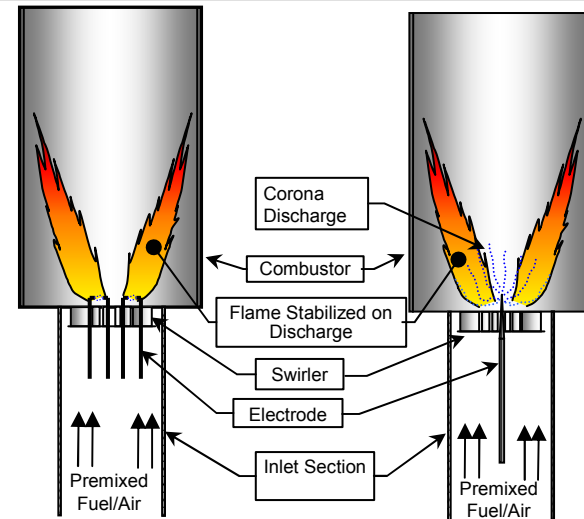
- Government: NASA/GRC
- URETI: Low Emission Combustor Studies, URETI/MSFC studies in weakly ionized gases
- Industry: General Electric Aircraft Engine Co.

Proposed Approach:

- Determine minimum power for stable arc/corona discharge, optimize discharge design, and investigate flame stabilization by plasma generated species
- Simulations of plasma formation near discharge, its interaction with turbulent flames, validation with data

NASA Relevance/Impact:

- **Low emission** and **stable** lean combustion system
- Advance predictive capability to study plasma-flame interaction in realistic system, **prediction of emission** under varying conditions

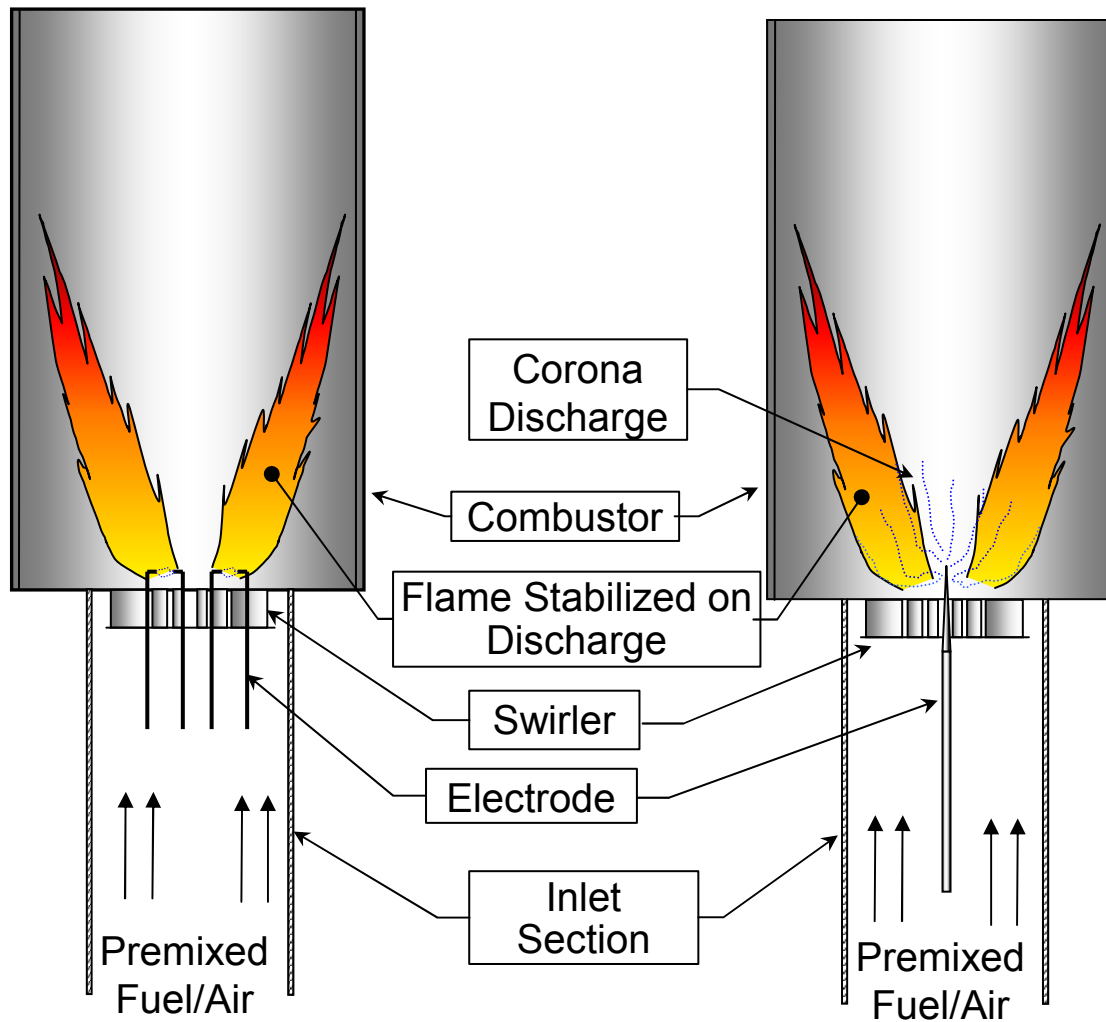


Milestones/Accomplishments (first 2 years):

- Determine minimum arc/corona discharge strength
- Compare effectiveness of arc/corona discharge
- Investigate optimal radical species for flame stabilization and fast arc initiation
- Validation of 3D plasma flow predictive tool
- Application of plasma simulation model to experimental arc device
- Optimization of plasma discharge system using combined numerical and experimental studies

Plasma Augmented Combustion Concept

Jagoda and Menon (Georgia Tech)



Plasma Augmented Combustion Proposed Approach

Jagoda and Menon (Georgia Tech)

- **Stabilization of combustion** in lean-blow off regime is critical to extend flammability limit and for “flameless” combustion mode
- **Experimental:**
 - Develop low-power plasma discharge/jet systems
 - Compare performance of arc and corona discharge
 - Identify ion/radical species that provide best flame-holding
 - Develop fast arc initiation procedure
 - Determine optimum injector distribution in combustor
- **Numerical**
 - Develop an advanced 3D plasma-fluid-turbulence simulation model with realistic kinetics using ISAT and ANN
 - Apply simulation tool to the experimental device to understand the physics of flame stabilization by plasma discharge
 - Provide insight into design and help optimize the system
 - Use simulation model to study performance of combustion system near lean blow out with and without plasma enhancement

Enabling Technologies - Diagnostics and Sensors

Wireless MEMS Sensors for Harsh Environments

Allen (Georgia Tech)

Science & Technology Objective(s):

- Demonstrate **passive, wireless MEMS sensors** in **harsh environments** ($T > 600^{\circ}\text{C}$)
- Demonstrate **sensing of p, T, chemical species**

Collaborations:

- Government - NASA, Air Force
- URETI - Wang, Jagoda, Glezer, Sankar
- Industry - United Technologies, P&W (potential)
- Synergism with existing programs - Leverage previous MURI program results

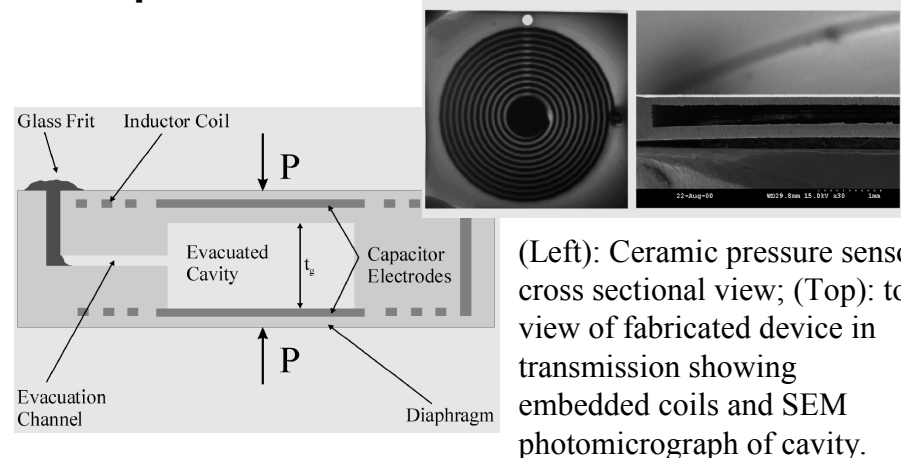
Proposed Approach:

- Remotely sense physical parameters at high T using self-packaged, passive wireless sensors
 - complexity in high T environment kept to a minimum
 - no circuits, power supplies or contacts in high temperature environment
 - since sensing system is wireless, motion of sensor through medium is possible

NASA Relevance/Impact:

- **Real-time engine performance adjustment and control**
- **Health monitoring and maintainence**

Concept:



(Left): Ceramic pressure sensor cross sectional view; (Top): top view of fabricated device in transmission showing embedded coils and SEM photomicrograph of cavity.

Milestones/Accomplishments (Years 1-2):

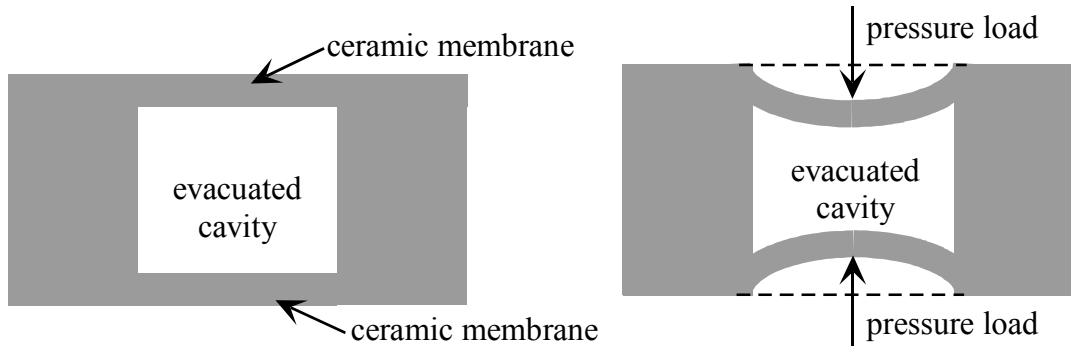
Currently wireless pressure sensors have been demonstrated to operate at temperatures up to 550°C . Over the next two years we will:

- Identify existing materials most suitable for chemical and temperature sensing (6 months)
- Develop MEMS-compatible schemes for incorporation of these materials into passive wireless sensing schemes (1 year).
- Extend operating temperature range of sensors above 600°C (18 months)
- Incorporate chemical and temperature sensing schemes into passive wireless sensors (24 months)

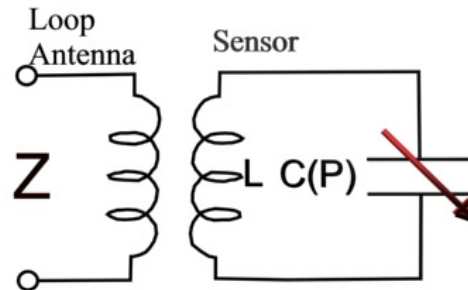
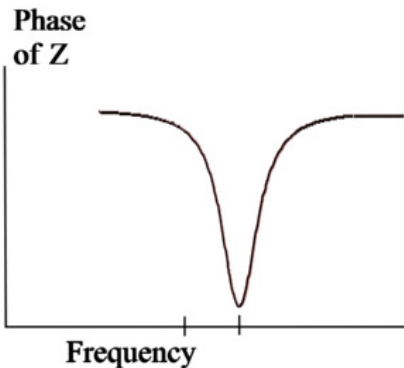
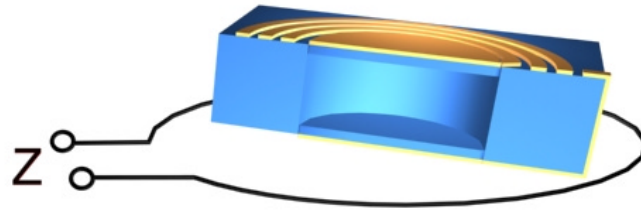
Wireless MEMS Sensors for Harsh Environments

Wireless Sensing (Pressure Example)

Allen (Georgia Tech)



$$f = \frac{1}{2\pi\sqrt{LC(P)}}$$



- Utilize well-developed hermetic ceramic laminate technology from the electronics packaging industry
- Embed passive elements, sensing elements, antennas and/or movable microstructures on or into the laminate
- Passive wireless technology - no batteries, circuits in harsh environment ($T > 600^{\circ}\text{C}$)

Wireless MEMS Sensors for Harsh Environments

Proposed Approach

Allen (Georgia Tech)

- Sense variety of physical phenomena of interest to engine and vehicle performance and health:
 - **Chemical monitoring** - incorporation of resistance-sensitive or dielectric-sensitive materials and nanomaterials into sensors whose properties change in the presence of appropriate chemical species
 - **Thermal monitoring** - utilize change in resistance of metals, e.g., Pt, to sense changes in resonant circuit
 - **Peak thermal monitoring** - utilize irreversible changes in conductors, e.g., melting, to produce irreversible shifts in resonance behavior when peak temperatures are exceeded
- Utilize ceramic laminate technology for non-sensing purposes, e.g., micro-scale fuel distribution/mixing

Enabling Technologies - Diagnostics and Sensors

Turbulence and Hot Streak Diagnostics in Turbines

Dunn (Ohio State) and Mavris (Georgia Tech)

Science & Technology Objective(s):

- Determine importance of **free stream turbulence on heat transfer for a fully cooled turbine** stage
- Determine the **migration of hot streaks**
- **Incorporate** results into state-of-the-art **CFD** codes

Collaborations:

- Government - NASA and USAF
- URETI - OSU and Georgia Tech
- Industry -Honeywell, GEAE
- Synergism with existing programs - Honeywell & GEAE programs

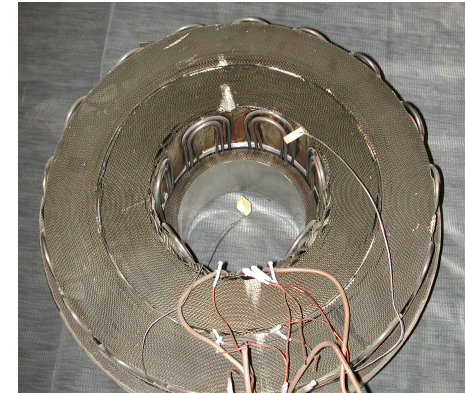
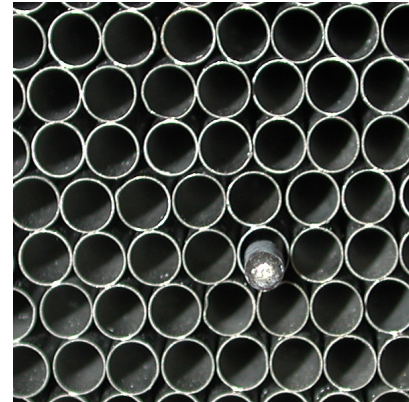
Proposed Approach:

- Construct turbulence generator for TFE 1042 stage
- Construct heater with hot streak capability for Honeywell TFE 1042 turbine stage
- Verify Tu intensity & scale and hot streak profile
- Perform measurement program

NASA Relevance/Impact:

- Impact of free stream turbulence on film cooled stage has not been experimentally verified
- Results will have significant impact on **HPT heat transfer prediction capability**

Tube Heater (L) & Honeycomb Heater (R)



Milestones/Accomplishments:

- Design and construction of turbulence generator to fix TFE 1042 rig hardware
- Design and construction (or modification to existing) of heater and hot streak generator
- Verify Tu intensity and scale generated by generator.
- Verify hot streak profile capability of heater
- Perform vane & blade heat transfer measurements in presence of turbulence generator and film cooling
Compare results with those in absence of turbulence

Turbulence and Hot Streak Diagnostics in Turbines

Proposed Approach

- Develop a revolutionary approach for measuring the characteristics of hot streak migration, turbulence intensity, and turbulence scale in turbine rigs
- For the development research program, utilize the existing honeywell TFE-1042 hardware & an adapted hot streak and turbulence generator instead of a fuel-fired combustor
 - actual engine combustor will be used late in the program
- Adapt MEMS instrumentation to vanes & blades of TFE-1042 to provide full-surface pressure coverage
- Incorporate results of investigation into state-of-the-art CFD codes
 - NASA National Combustor Code
 - National Engine Code Validation

Nanotechnology Nanomaterials for Sensors

Wang, Georgia Tech

Science & Technology Objective(s):

- Use an **aligned nanotube array as sensor for monitoring gas flow rate** in confined regions
- Fabricate nanosize **gas (species) sensors using semiconducting oxide nanobelts**

Collaborations:

- Government – Oak Ridge National Lab
- URETI – Peter Hesketh

Proposed Approach:

Gas flow sensor with aligned carbon nanotubes

- Step 1: Synthesizing aligned nanotube arrays
- Step 2: Building the set up for field emission measurement under flowing gas environment
- Step 3: Testing the device for engine applications

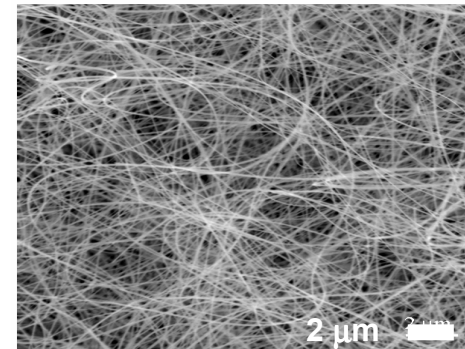
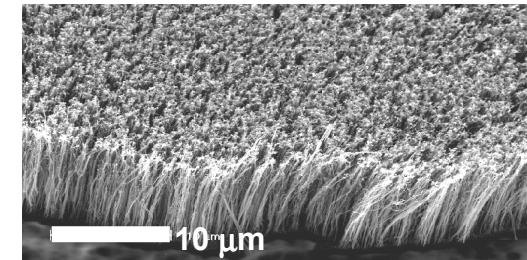
Gas species sensor w/ semiconducting oxide nanobelts

- Step 1: Synthesizing oxid nanobelts (ZnO)
- Step 2: Building the electrodes using e-beam lithography
- Step 3: Testing the device for gas sensor

NASA Relevance/Impact:

- In-situ real time monitoring of gas flow and gas composition for **improved engine control, reduced emissions, health monitoring**

**Aligned
Carbon
Nanotubes**



**Semiconducting
Oxide
Nanobelts**

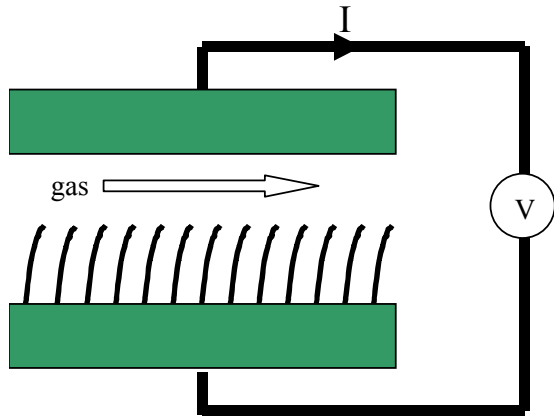
Milestones/Accomplishments:

	First	Year	M1	M2	M3	M4	M5	M6
1	Synthesis of aligned carbon nanotubes							
2	Synthesis of oxide nanobelts							
			M7	M8	M9	M10	M11	M12
3	Building set-up for field emission testing							
4	Building devices using nanobelts							

Nanomaterials for Sensors: Gas Flow Sensing Concept and Proposed Approach

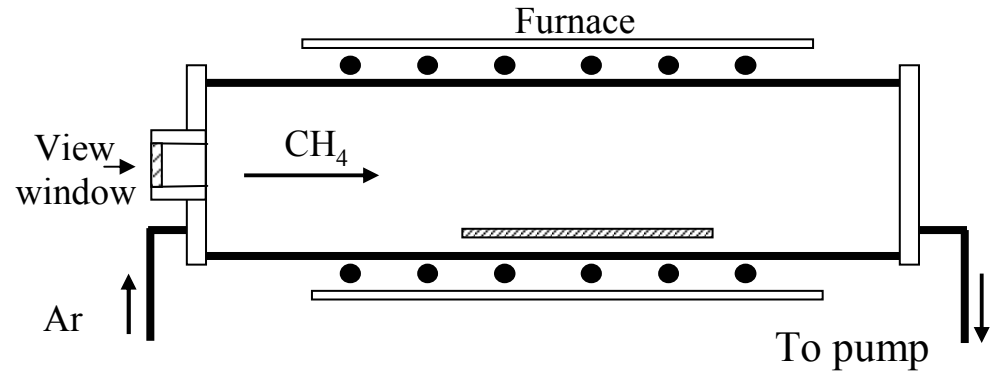
Wang, Georgia Tech

Sensor Concept and Testing



- Emission current changes with distance between tips of nanotubes and counter electrode
 - emission current should drop as nanotubes are bent by flow
- Monitor emission current and correlate to gas flow rate

Synthesis of Nanotubes

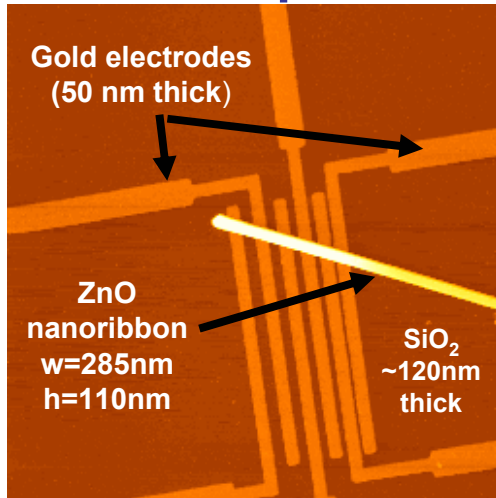


- Deposit Fe/Ni catalyst particles onto a ceramic substrate
- Grown carbon nanotubes by decomposition of CH_4 at high temperature
- Control temperature and gas flow rate to optimize the alignment

Nanomaterials for Sensors: Gas Species Sensing Concept and Proposed Approach

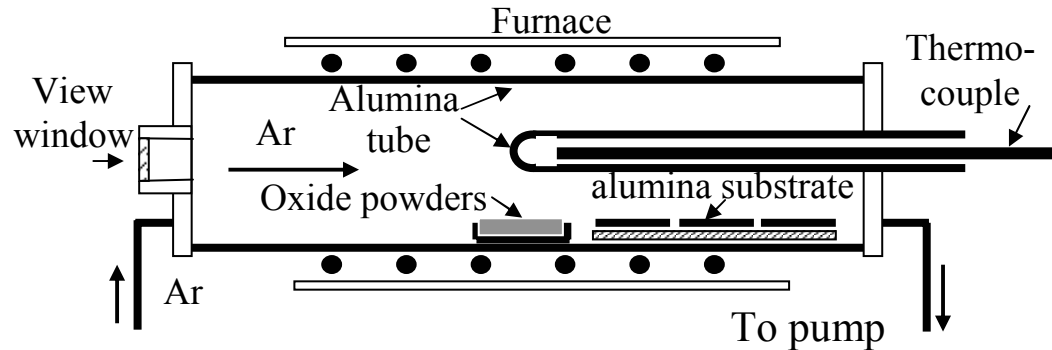
Wang, Georgia Tech

Sensor Concept and Testing



- Electrical conductance of nanobelt depends on type/amount of molecules adsorbed on its surface
- Build nanosensors out of individual semiconductive oxide nanobelts,
 - Make 2 probe measurements of electric conductance of single nanobelt wire under different temperatures and gas partial pressures

Synthesis of Oxide Nanobelts



- Place oxide powder as the source material in the crucible
- Thermal vaporization of the oxide followed by a deposition at the low temperature region results in the growth of nanobelts
- Control temperature and gas flow rate to optimize the morphology

Nanotechnology Nanometallic Fuel Additives

Seitzman and Wang, Georgia Tech

Science & Technology Objective(s):

- Develop **high energy density fuels with good combustion efficiency for high speed propulsion**
- Improve understanding of **combustion of nanometal fuel additives**

Collaborations:

- Government - AFRL
- Industry - Argonide
- URETI - Zinn, Jagoda, Menon
- Synergism with existing programs - Current nanometal solid propellant studies (300-2000 psi)

Proposed Approach:

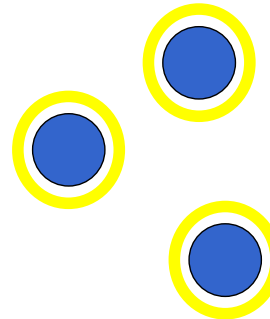
- Combine nanoscale and microscale metal particles with a liquid to form a fuel gel that gives high combustion efficiency and a compact reaction zone
- Use JP fuel and burn at elevated pressure

NASA Relevance/Impact:

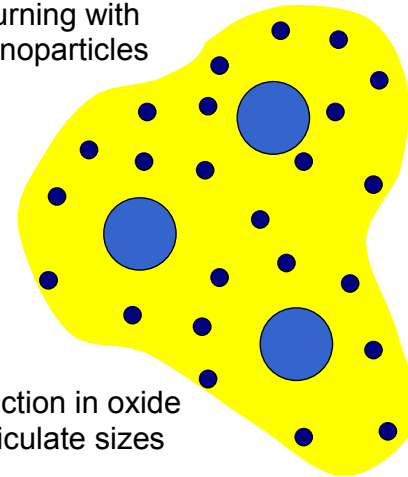
- **Reduce fuel tank size and combustor length** (reduce combustion time or reduce ignition delay) for high speed propulsion systems

Enhanced Combustion with Nanoparticles:

Isolated combustion
for conventional
particle sizes



Rapid group
burning with
nanoparticles



Reduction in oxide
particulate sizes

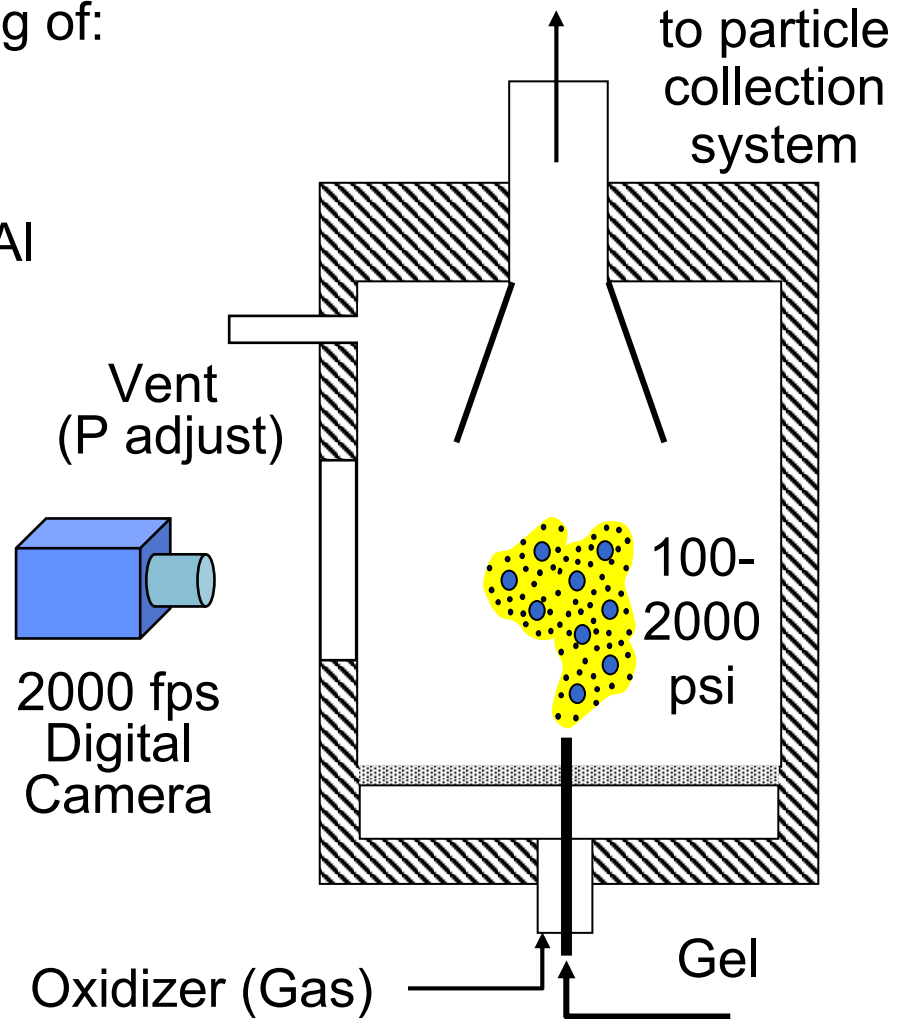
Milestones/Accomplishments (2 Years):

- Production of JP/Al gels with different Al particle size distributions
- Characterization of gel combustion to identify enhanced combustion due to group particle interactions with nanoparticles
- Characterization of combustion efficiency through residual particle analysis

Nanometallic Fuel Additives Metal Gel Studies

Seitzman and Wang, Georgia Tech

- Burn small samples of gels consisting of:
 - conventional Al particles and JP
 - nano-Al particles and JP
 - mixtures of nano & conventional Al
- Compare combustion times
- Characterize nanometallic fuel additives and residual combustion particles (oxides & unburned Al) by high-resolution TEM
- Characterize chemical composition of the residuals by analytical techniques
 - determine metal combustion efficiency



ENABLING TECHNOLOGIES - Continued

- Pursue basic technology areas with potential applications to wide range of aeropropulsion issues
- **Actuators**
 - Combustion driven actuators for mixing control
 - Plasma augmentors for combustion
- **Diagnostics and MEMS Sensors**
 - Passive, wireless MEMS sensors
 - Turbulence and hot streak diagnostics in turbines
- **Nanotechnology**
 - Nanomaterials for sensors
 - Nanometallic fuel additives

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NASA Glenn Research Center

Jim Williams

11/18/02

Improved Performance and Reliability Materials

Tasks:

- Materials Support for Performance and Life Methods Modeling
 - Properties: typicals and minimums
 - Materials Characterization
- Higher T_3 and T_{41} Capability
 - Airfoil Materials
 - TBCs
 - Disk Materials (to be added later or funded elsewhere)
- Low Emission Combustor Materials

Benefits of Further Improvements

Reliability

- Longer range twin engine aircraft
 - ETOPS now standard – extend ETOPS approval
 - Lower maintenance cost
- Lower operating cost
- Improved fleet management (UER $\approx 0.08\%$)

Performance - Lower Fuel Consumption (SFC)

- Longer range
- Lower operating cost

Environmental

- Lower emissions and noise

Higher T's Require Improved Materials

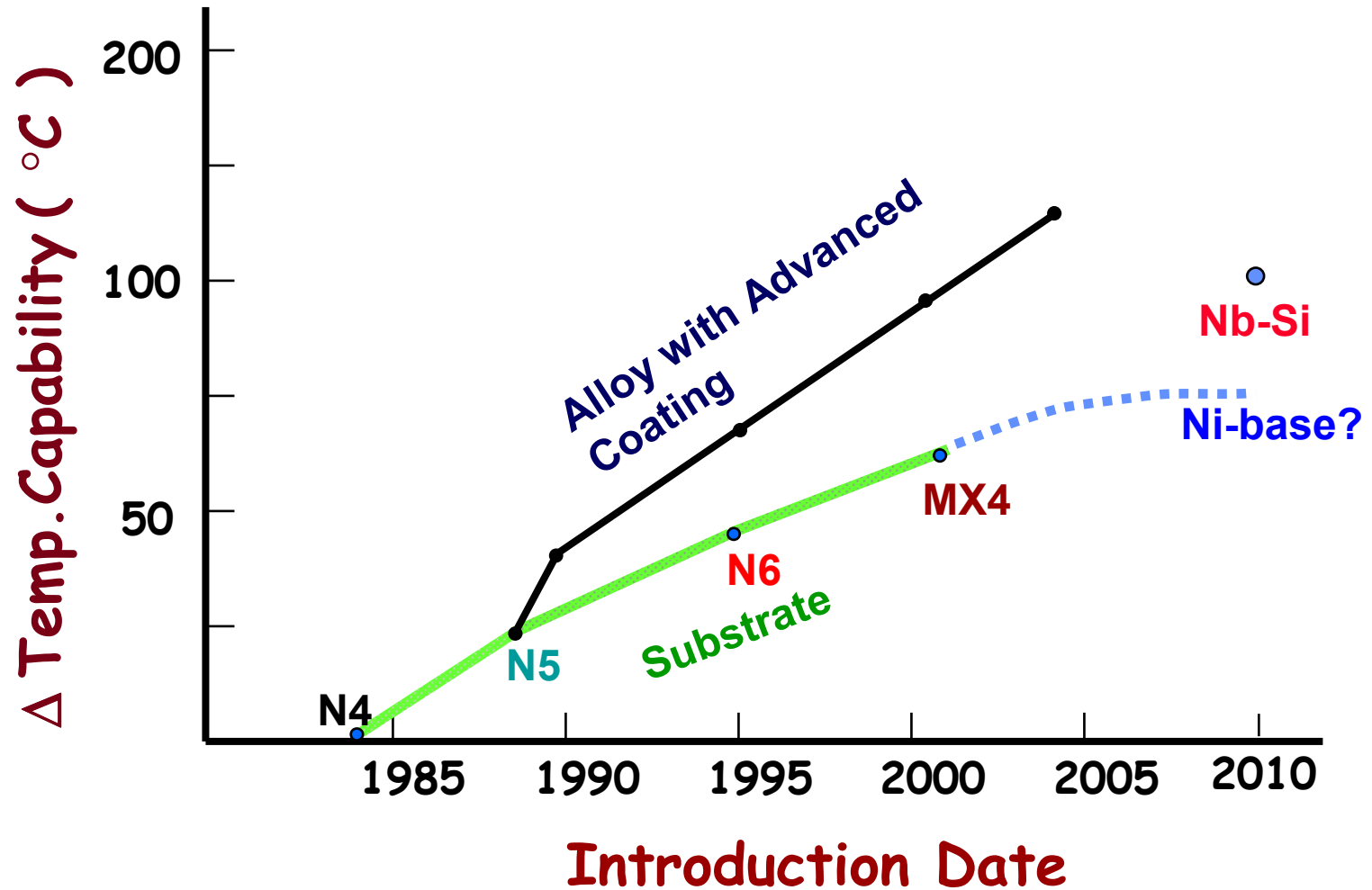
Important “Rules of Thumb”:

- **$55\text{ }^{\circ}\text{C } \Delta T_3 \approx 4 - 5\% \text{ SFC}$**
- **$55\text{ }^{\circ}\text{C } \Delta T_3 \approx 50\text{ }^{\circ}\text{C } \Delta T_{41}$**

- This requires better disk and turbine blade materials
- Approximate cost of introducing new disk material is \$35M (this is a major decision)
- Approximate cost of introducing new turbine blade material is \$10M (assumes minor castability changes)
- If T_3 and T_{41} are high enough:
 - improved casing materials
 - improved compressor blades (cast Ni-base alloys?)

More fuel efficient engines come at a substantial cost

Airfoil Alloy Trendline



Near-Net Shape Refractory Intermetallic Composites

M. J. Mills, H. L. Fraser and J. C. Williams , MSE / OSU

Science & Technology Objective(s):

- Pursue a revolutionary advance in the performance and fabrication of turbine blade materials
- Utilize the laser engineered net-shape (LENS™) process to produce Nb-Ti-Si in-situ composites

Collaborations:

- Government - NASA Glenn Research Center
- Industry - GECRD (Bernard Belway), Optimec (R. Grylls), Reference Metals (T. Cadero)
- Synergism with existing programs - Center for Accelerated Maturation of Materials (CAMM / OSU)

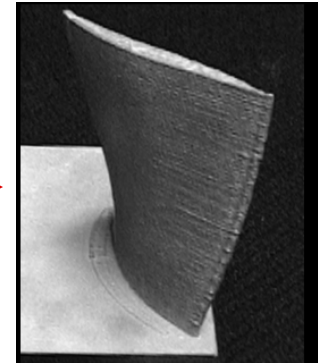
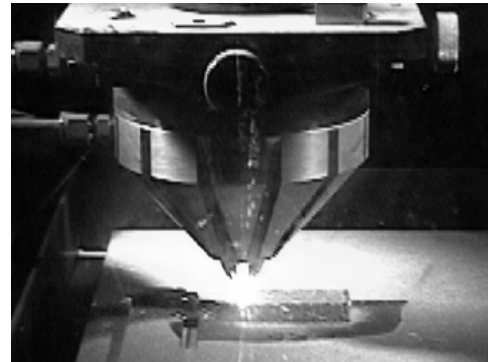
Proposed Approach:

- Using existing LENS™ facility (OSU), produce deposits from elemental powder blends
- Analysis of microstructure/mechanical/oxidation properties
- Optimization of composition/microstructure/properties via combinatorial approaches

NASA Relevance/Impact:

- Cost-effective route to improved high-temperature turbine engine components
- Complex, near-net shape and functionally graded structures can be produced

LENS™ to Produce Novel Microstructures and Components:

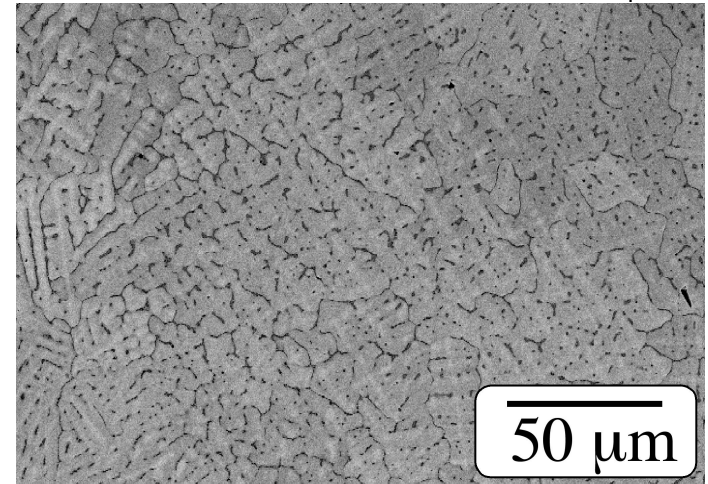
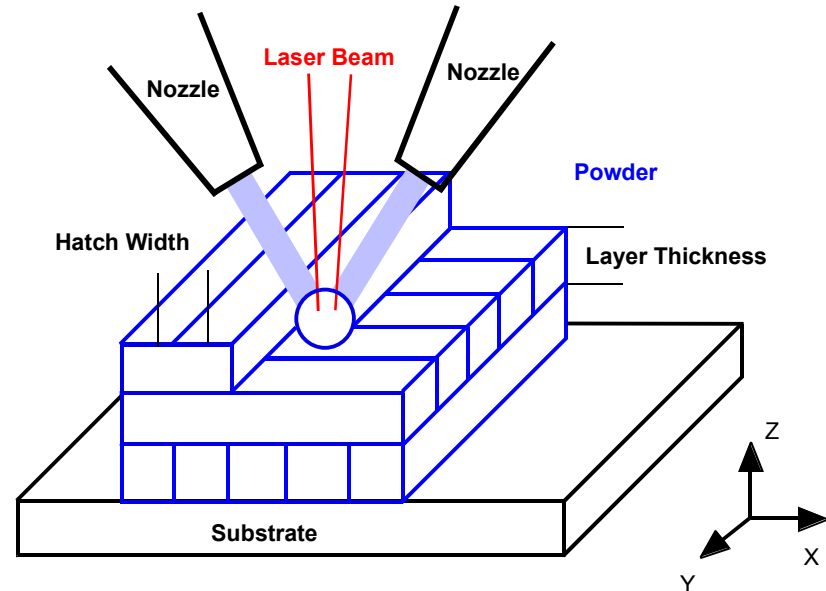


Milestones/Accomplishments:

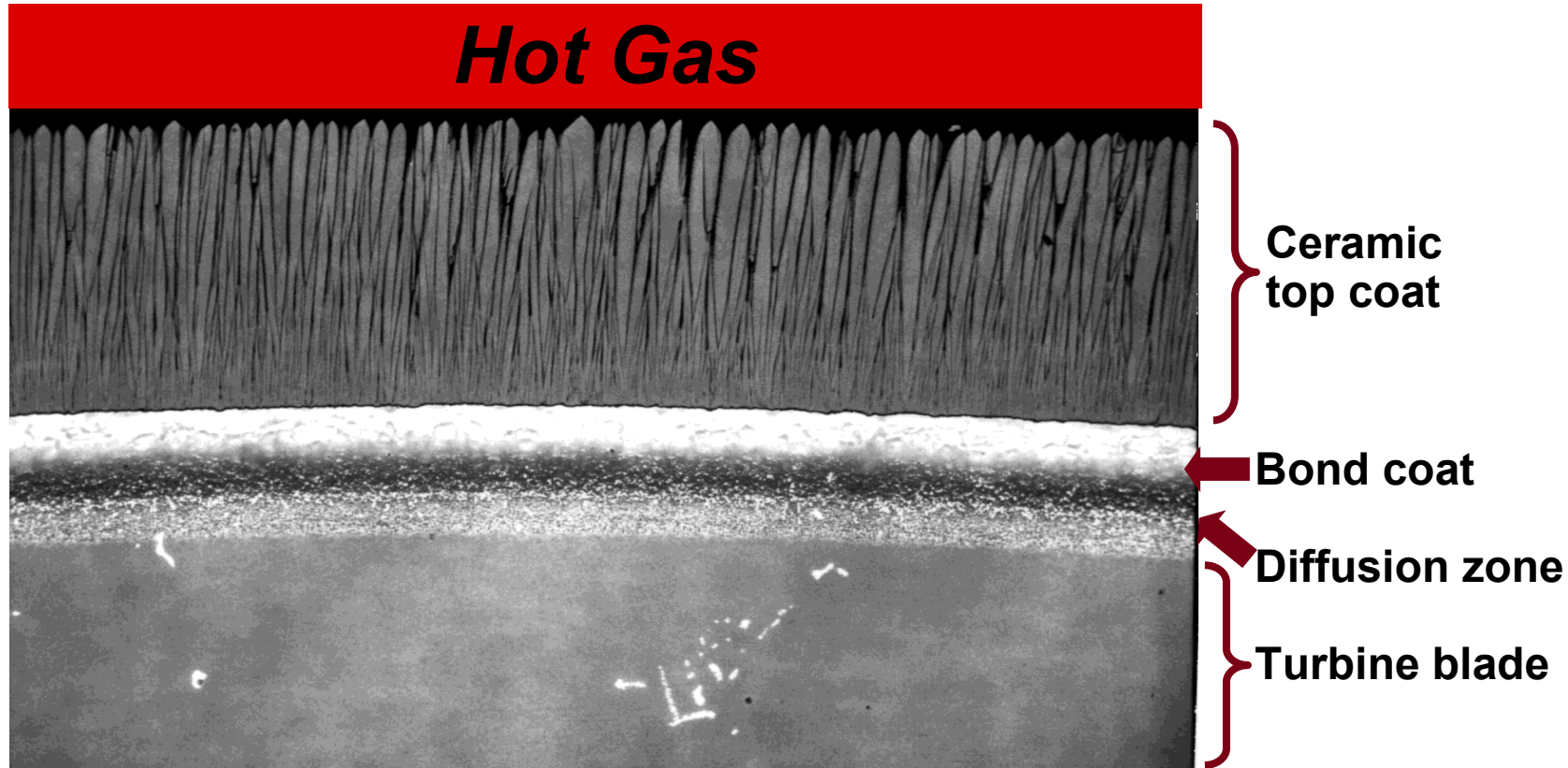
- Obtain suitable Nb powders and perform trial depositions
- Produce wide range of compositions in Nb-Ti-Si system for fabrication and detailed analysis
- Microstructure characterization using SEM/TEM/FIB techniques.
- Mechanical testing and oxidation studies as a function of composition.
- Use generated database to target promising compositions
- Explore compositionally graded structures.

Proposed Approach

- **Use existing LENS™ facilities in MSE/OSU.**
 - In LENS™, a focused laser light source is used as a heat source to melt a feed of metallic powder to build-up a solid, three-dimensional object
- **Advantages include:**
 - Complex, near-net shapes can be fabricated
 - Potentially attractive, non-equilibrium microstructures can be created
- **Novel approach utilizes *elemental* powder feedstocks since they are:**
 - Much cheaper than pre-alloyed powders
 - When phases formed have a negative enthalpy of mixing, can produce fine, dense and homogeneous microstructures
 - Graded compositions can be readily made
- **Already demonstrated ability to produce desirable microstructures in the Nb-Ti-Si-Cr alloy system**



Thermal Barrier Coatings



Key TBC Features:

- Columnar structure in top coat for spall resistance
- Oxidation resistant and adherent bond coat
- Bond coat compatible with alloy substrate

Enabling Technologies - Materials Higher T_{41} Materials – Thermal Barrier Coatings

Mark Walter, The Ohio State university

Science & Technology Objective(s):

develop a comprehensive, systems-based model for thermal and environmental barrier coatings

Collaborations:

- Government – NASA - GRC
- URETI -
- Industry – GE Aircraft Engines
- Synergism with existing programs -

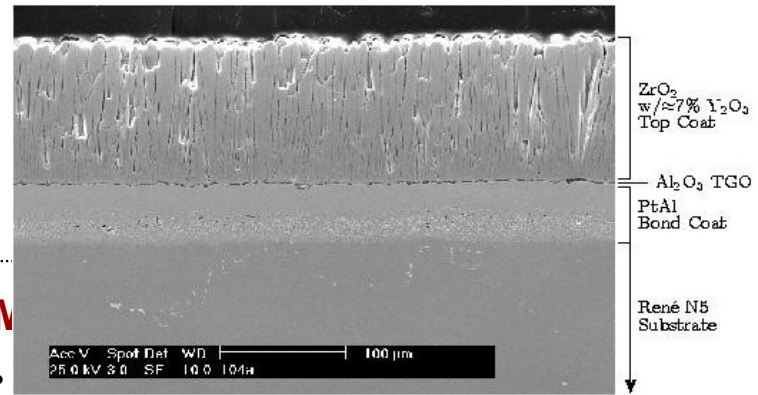
Proposed Approach:

- Start with EB-PVD coatings with PtAl Bond coats and superalloy substrates
- Compare simulations to existing data.
- Simulate top coat materials with varying degrees of compliance CMAS depositions.

NASA Relevance/Impact:

- Improved TBCs are an integral part of higher T_{41}

TBC Example



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- Incorporation of wrinkling of the bond coat/TGO/top coat interface
- Include finite elements to enable damage propagation.
- Study top coat sintering and CMAS deposits.
- Compare simulations to experiments.

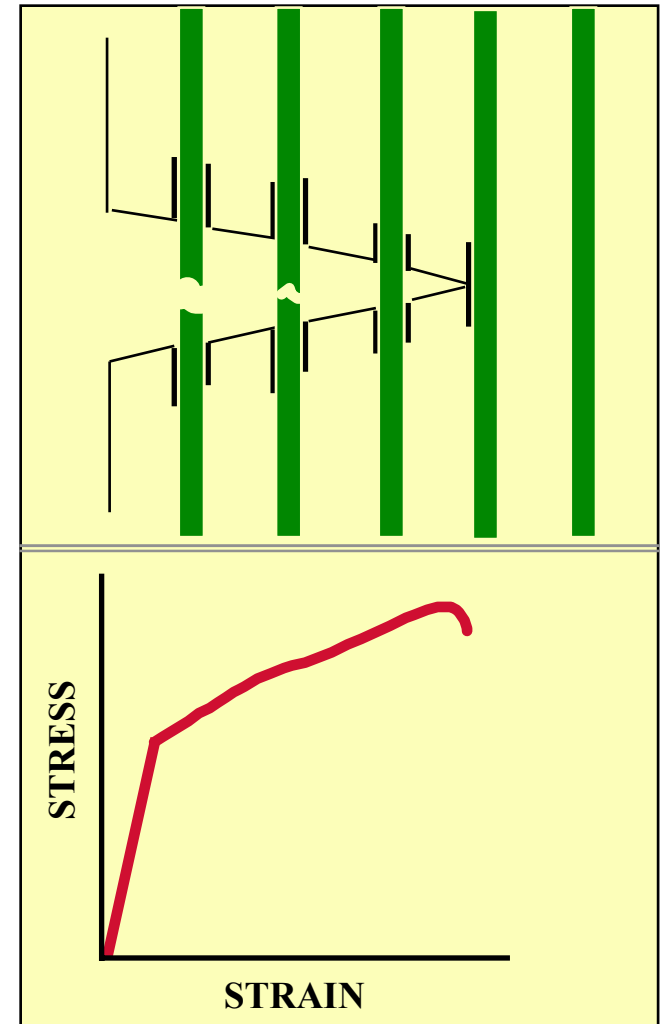
Proposed Approach

- Begin with models of EB-PVD coatings with PtAl Bond coats and superalloy substrates which incorporate phase evolution, thermally growing oxide, and damage evolution.
- Compare simulations of isothermal and thermocyclic loading to existing experimental data.
- Simulations of top coat materials with varying degrees of compliance and accounting for sintering and CMAS depositions.
- Investigate alternative top coat materials and structures through materials design simulations.
- To design an optimal set of residual stresses and crack compliances for improved coating performance and life.

Desirable CMC Characteristics

- o **High Temperature Capability**
 - Environmentally Stable Constituents
- o **Thermal Shock Resistance**
 - High Thermal Conductivity
 - High Matrix Strength
- o **Damage Tolerance**
 - Continuous Fiber Reinforcement
 - Retention of Fiber Dominated Behavior
- o **Affordable**
 - Multiple sources
 - Common fiber type?
- o **Good Shape Forming Capability**
- o **Environmental Durability**

No affordable production sources today



Demonstrator CMC Combustor Inner Liner



- Successfully Completed Rig Testing With SiC/SiC CMC Inner Liner
- Post-Test NDE Showed No Signs of Material Degradation
- Rig Test Conditions;
 - 15 Hours at F110 Conditions
 - 40+ Hours at IHPTET Conditions
- Next Step-ATEGG Core Engine Test Initiated

CMC's incorporating a Co-Continuous Ceramic-Metal Matrix Component

Glenn Daehn, & Jim Williams, The Ohio State University

Science & Technology Objective(s):

- Develop new class of high temperature ceramic-metal composites. Will possess: low density, good toughness, high temperature strength, low processing cost.

Collaborations:

- NASA- Glenn (background/constraints re/CMC's)
- GEAE (background/constraints re/CMC's)
- BFD, Inc. (Processing technology)

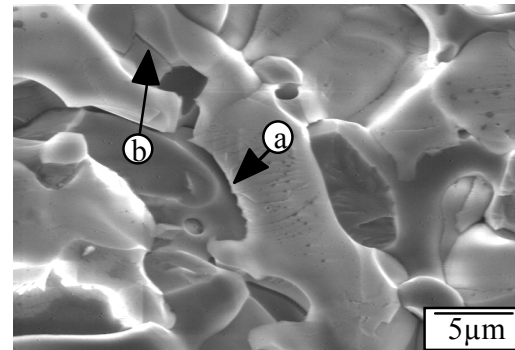
Proposed Approach:

- Visit CMC experts at NASA-Glenn, GEAE and WPAFB - detail project design and ensure relevance.
- Design new desired microstructure involving continuous ceramic and metal phases
- Produce materials and measure properties

NASA Relevance/Impact:

- Conventional superalloys are reaching fundamental performance limits. New materials proposed that can provide higher operating temp., low density, without poor toughness and high cost of similar materials.

Example- Fracture Surface, Ni Al - Al_2O_3 co-continuous composite:



Lighter phase is NiAl. Composite tougher than constituents. Debonding (a) and deflection (b) shown here.

Milestones/Accomplishments:

- CMC state of the art report and detailed project objectives (after consultation with collaborators)
- Microstructural objectives and processing plan for new materials.
- Demonstrate production of new materials.
- Measure and report properties.

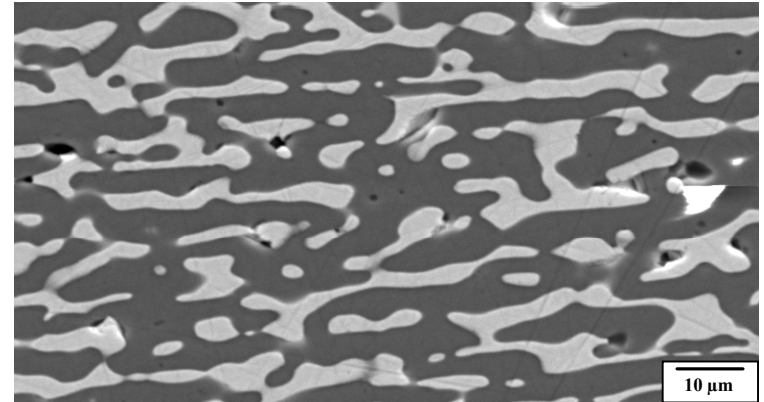
Proposed Approach - Reactive Infiltration

Established Processing Scheme

- SiO_2 shaped precursor is immersed in liquid Al at 1100°C .



- As 2 moles of Al_2O_3 occupy less volume than 3 moles of SiO_2 , porous alumina is created and infiltrated!
- Process is net-shape.



Example: NiAl + Al_2O_3 composite.
Dark phase is ceramic (Al_2O_3).

Enhancements in this program

- Use high melting metal or intermetallic to fill pores in ceramic instead of aluminum.
- Add continuous ceramic fibers as well.

Summary and Take-aways

- Substantial progress in aero engine performance in past 25 years
 - Materials have played a major role in this
- Further improvements will require major materials investment in Ni-base disks and blades
 - Continued improvements in Ni-base turbine blades open to question
- Lower emissions combustors require better liner materials
 - CMCs are the best bet
- Opportunities in other lighter weight and higher temperature materials await market pull and industrial base investment
 - Should do enabling work now

Summary of Progress – past 25 years

- Thrust:weight has increased ~2.5X
 - Higher operating temperatures
 - Lighter weight structures and materials
- Time on wing has increased ~40X
 - Reduced inspections
 - Improved combustor pattern factors
 - Improved hot section materials
- Fewer delays, cancellations, unscheduled removals and in-flight shut downs
 - Broad use of FADEC
 - Better bearings
 - Improved controls and accessories
 - More EGT margin
 - More stall margin (margin varies between engine companies)
 - ETOPS now routine

Disk Task to be funded elsewhere

Funding Possibilities:

- FAA additional funding
- Ohio/NASA/USAF Propulsion 21
- GE company funded program

Advanced Disk Alloy Goals

- Density < Predecessor (.297 vs. .302)
 - Tensile (UTS) \cong same
 - Creep/Rupture (+30°C improvement)
- } Lighter Weight
- LCF \cong same until 650°C; Superior >650°C
 - SPLCF > same
- } Enables Higher T3
- Cyclic FCGR \cong same
 - Dwell FCGR 50X slower (+80°C Capability)
- } Superior Probabalistic Life

Improved stability alloy enables high temperatures & long hold times use while maintaining lower temperature properties

Advanced Disk Alloy Capability

